Spillway Erosion

Best Practices in Dam and Levee Safety Risk Analysis

Part D – Embankments and Foundations

Chapter D-2

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US Army Corps of Engineers®

U.S. Department of the Interior Bureau of Reclamation

Department of Energy Federal Energy Regulatory Commission

TVA

Objectives

- Understand the mechanisms that affect spillway erosion
- Understand how to construct an event tree to represent spillway erosion
- Understand the considerations that make this potential failure mode more/less likely
- Understand the differences and limitations of the models used to quantify erosion of rock and soil

Key Concepts – Spillway Erosion

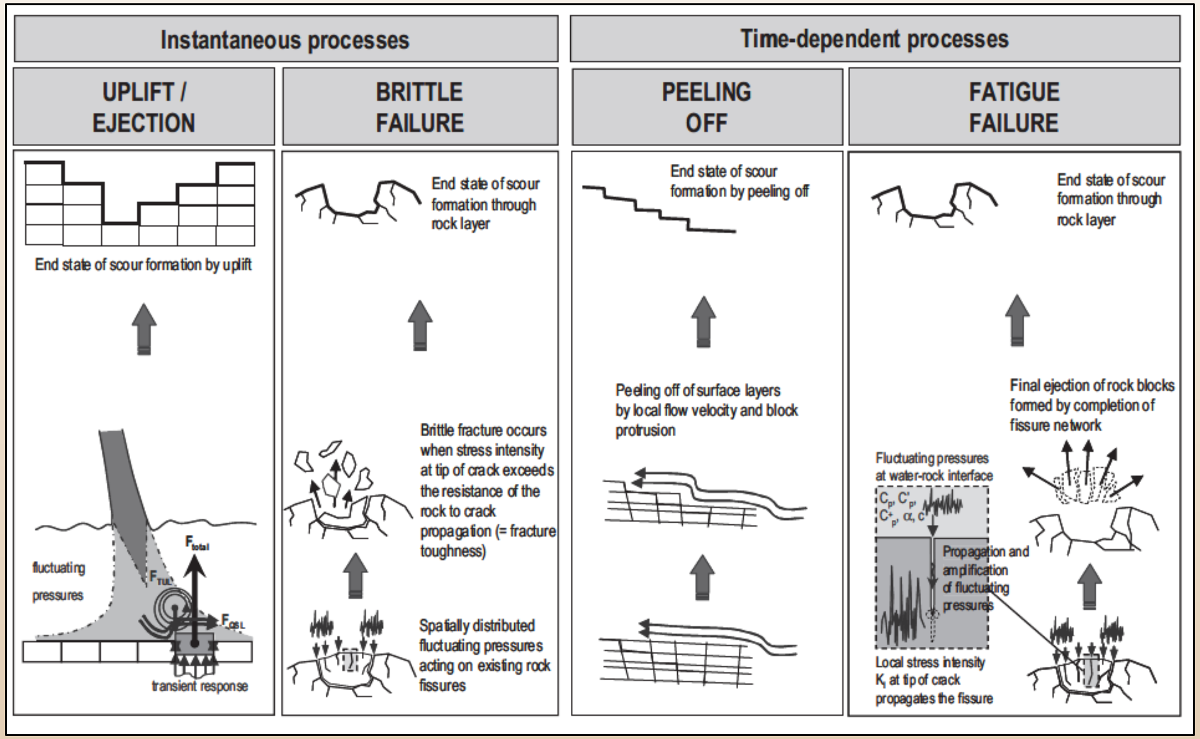
- Recognize that the failure progression is duration dependent (judgement required in evaluating rate of erosion, duration of loading, etc.)
- Understand the difference between erosion of a uniform material and that of a varied geology
- There are multiple methods available for estimating erosion/scour potential
- Scour is complicated and cross-disciplinary
- This failure mechanism can be linked to the likelihood of other failure modes (e.g. control section stability, spillway chutes, tunnels and stilling basins)

Outline

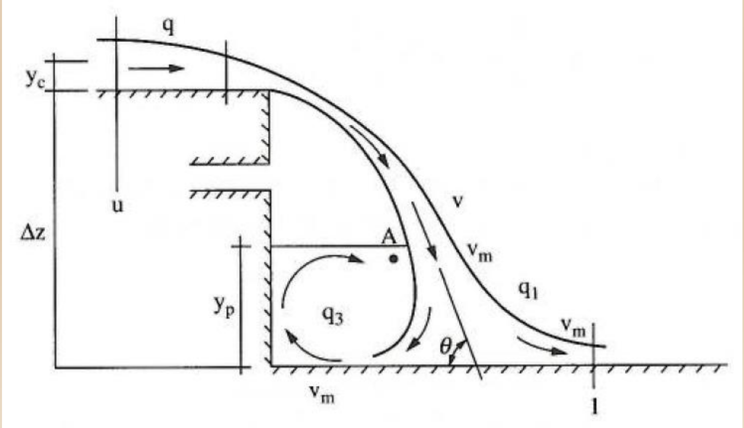
- Overview of the Process
- Case Histories
- Typical Event Tree
- Key Factors Affecting Vulnerability
- Analytical Methods
- Crosswalk to Other Potential Failure Modes

Overview of the Process

Spillway Erosion/Scour Process



Bollaert (2010)

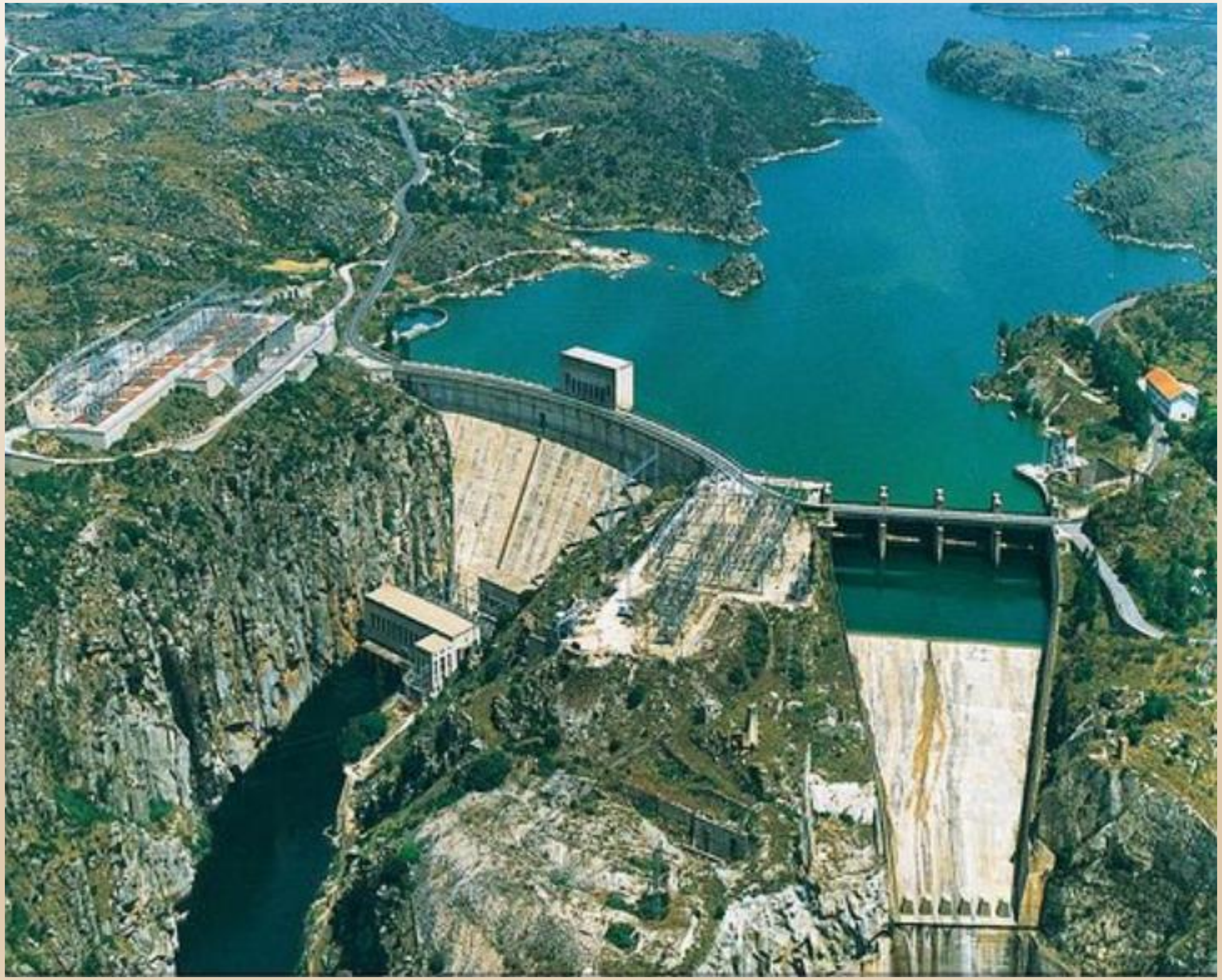


Annandale (2006)

- Turbulence Production
  - Impinging Jet
  - Submerged Jet
  - Back Roller
  - Hydraulic Jump
  - Boundary Eddy Formation
- Particle Detachment
  - Brittle Failure
  - Fatigue Failure
  - Block Removal (Ejection or Peeling)
  - Abrasion
  - Tensile Block Failure
- Particle Breakup/Transport
  - Armoring
  - Breakup
  - Transport

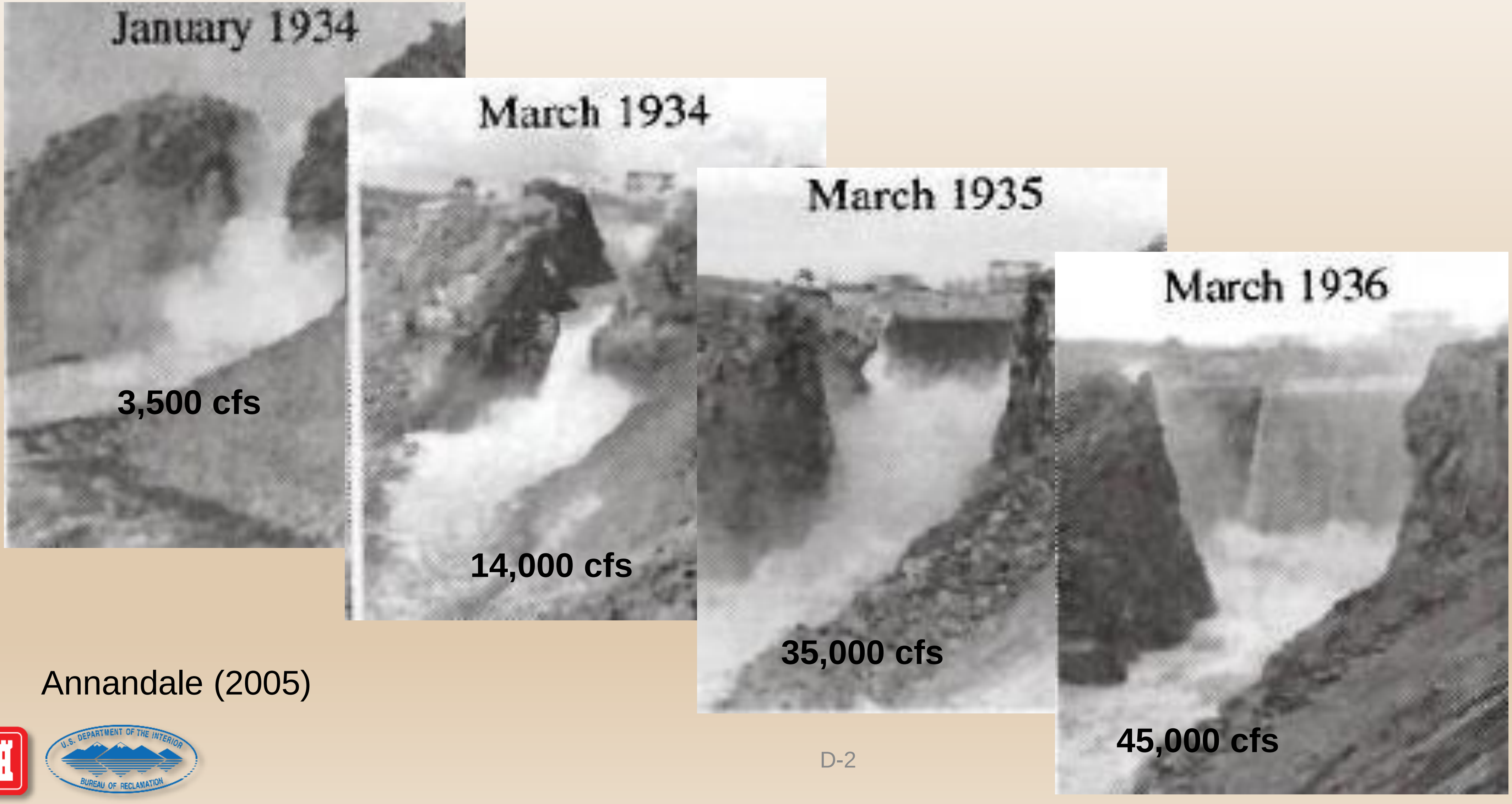
Case Histories

Ricobayo Dam Spillway



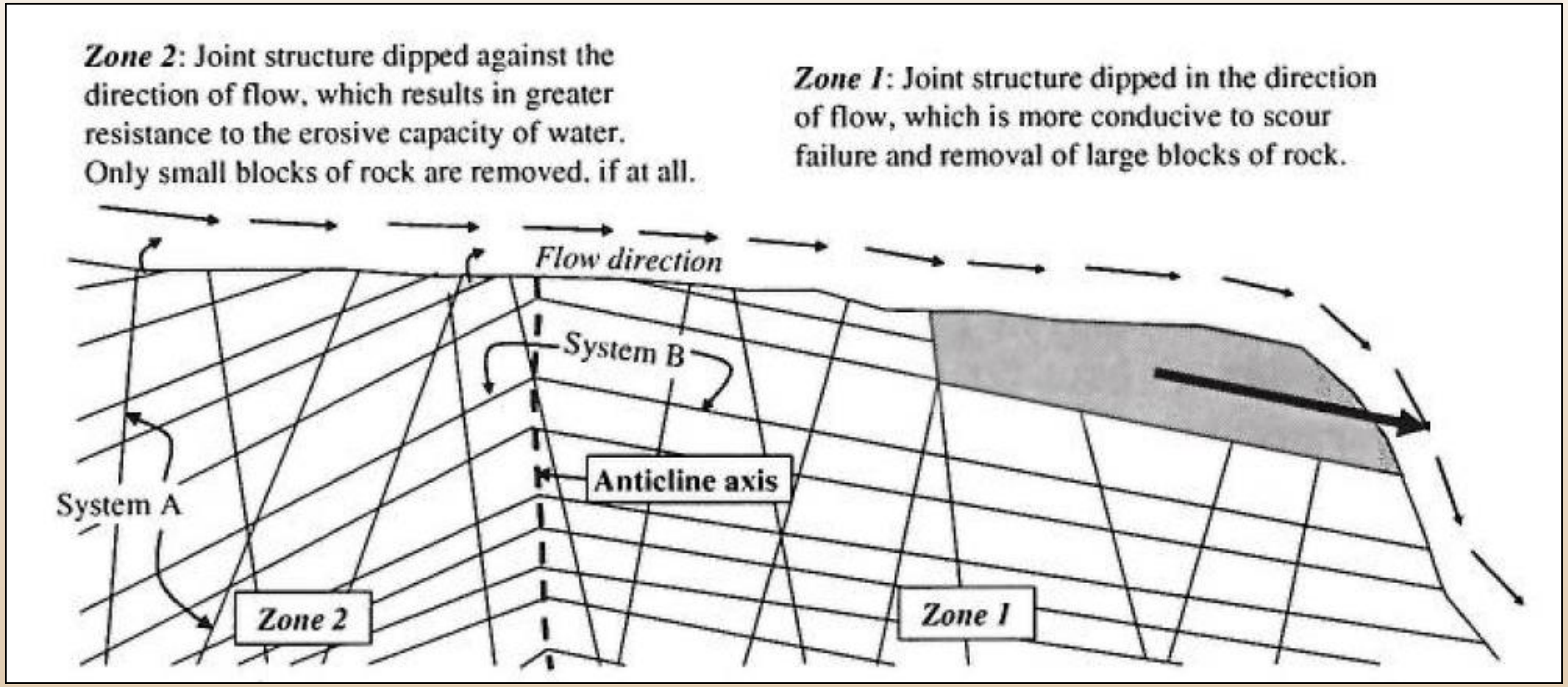
- Owned by Iberdrola
- Dam and Spillway Construction complete in 1933
- 320-ft Tall Arch Dam
- 1300-ft long Unlined Spillway Channel
- Spillway channel was open-jointed granite
- An Anticline and fault are located along the Chute

Ricobayo Dam Spillway



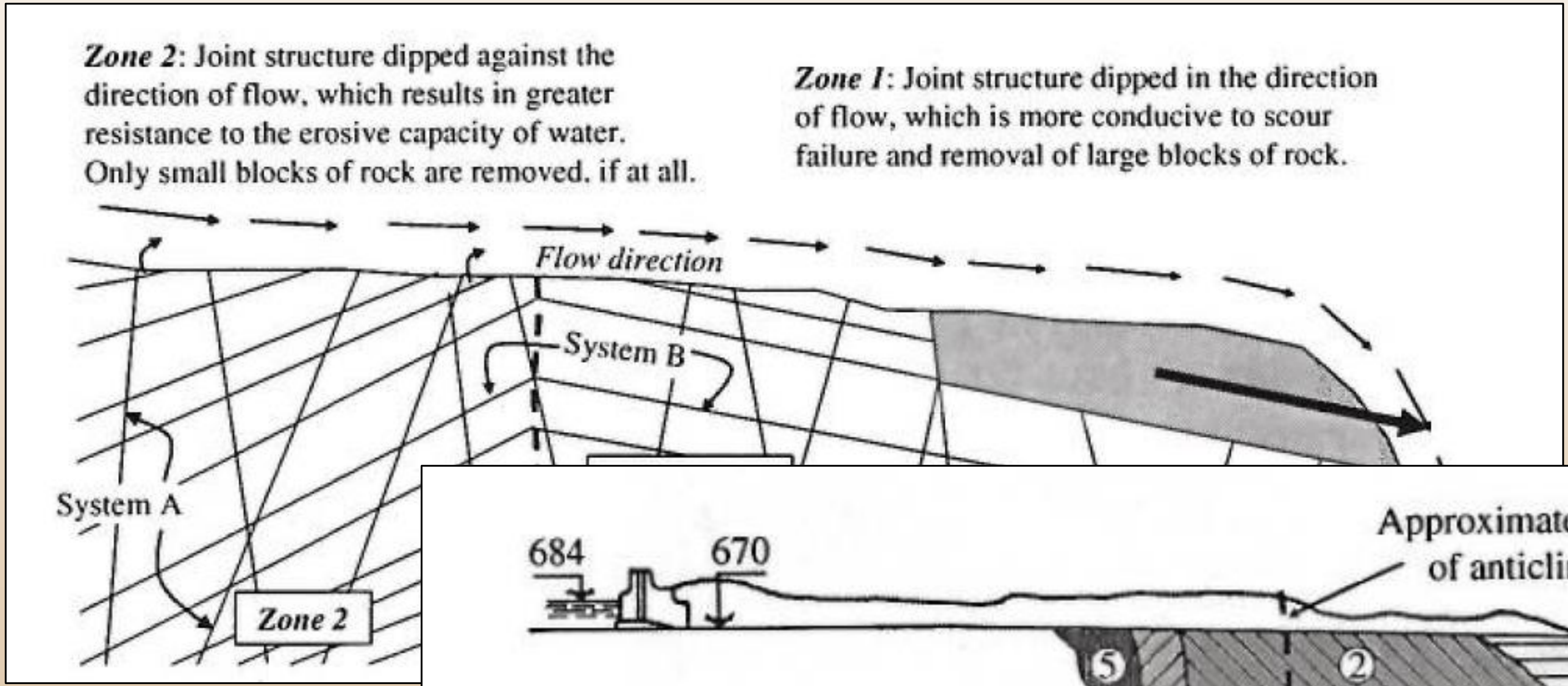
Annandale (2005)

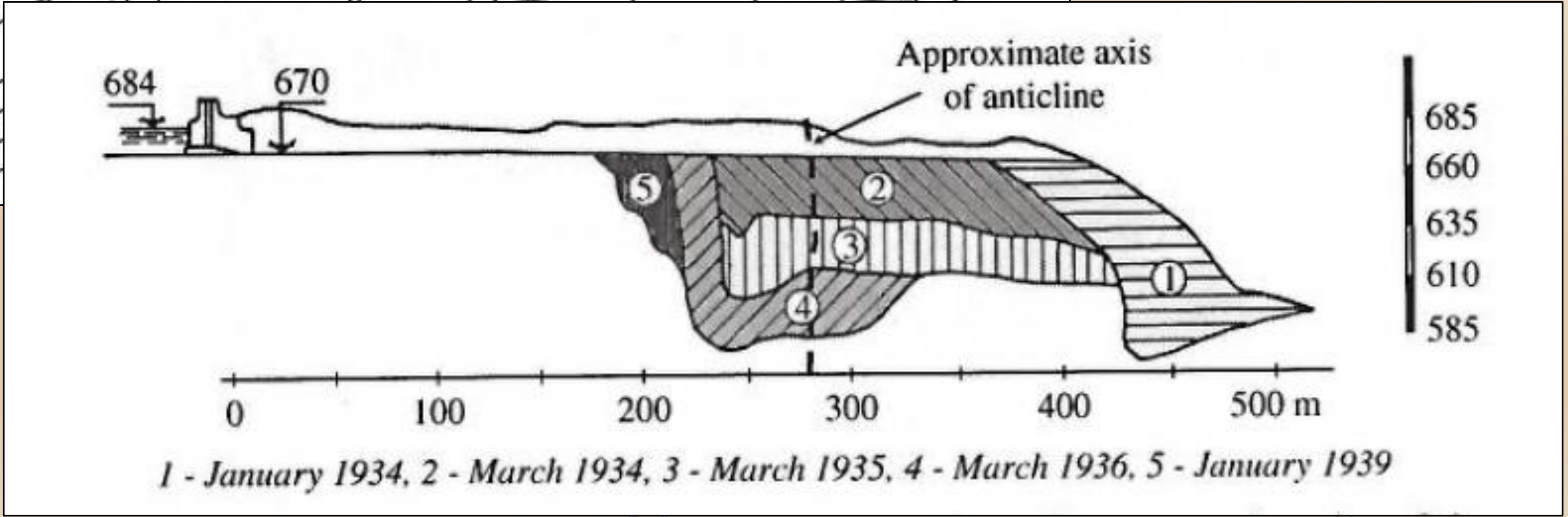
Ricobayo Dam Spillway



Annandale (2006)

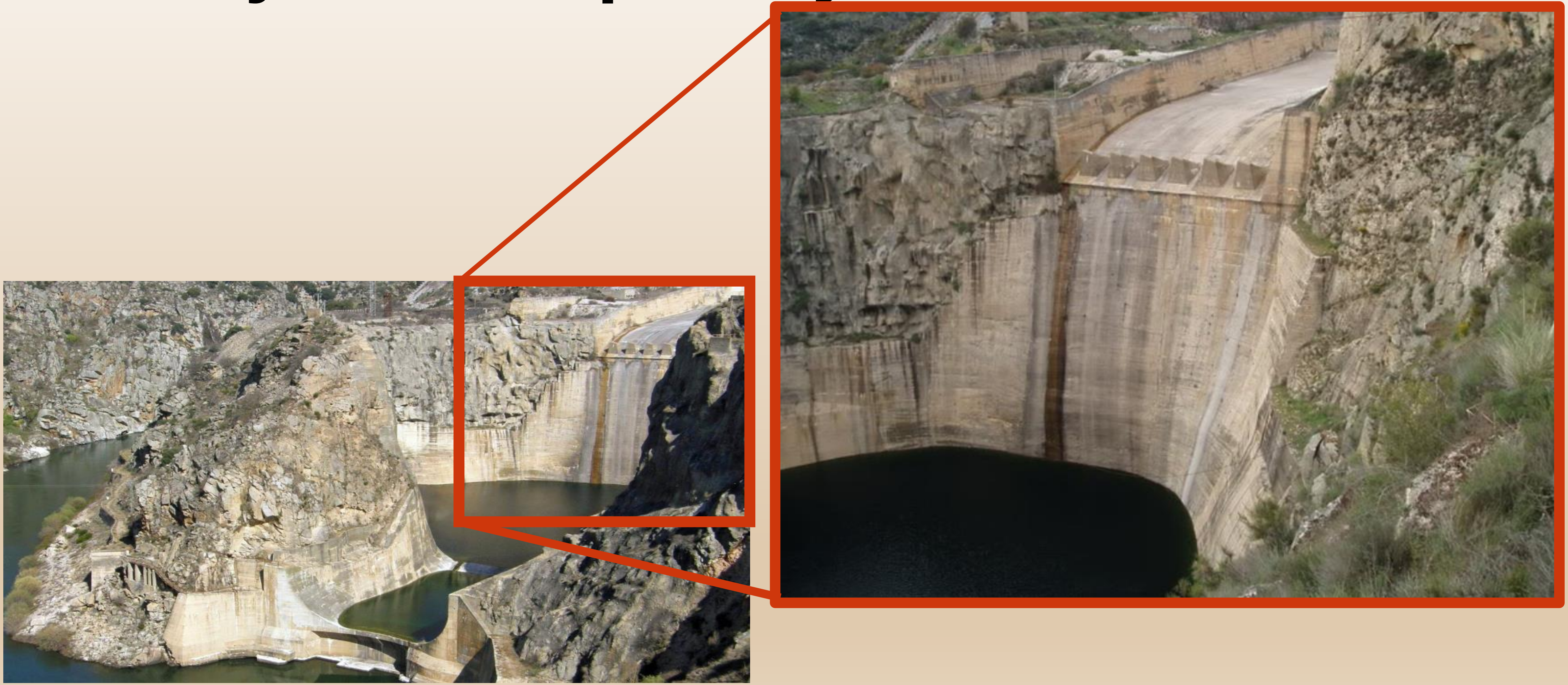
Ricobayo Dam Spillway





Annandale (2006)

Ricobayo Dam Spillway



Saylorville Dam Spillway

- USACE (Rock Island) Dam in Iowa, in operation in 1977
- Uncontrolled Ogee Weir and unlined downstream chute
- Spillway is comprised of gently dipping shales, calcareous siltstones, thin limestones, coal, and sandstone
- Spillway operated from the period of 18 June to 3 July 1984
- Flow was estimated at 9-precent of design discharge
- Severe Damage to the unlined spillway

Saylorville Dam Spillway

Figure 13. Downstream view of the severe erosion that occurred in the unstable portion of the Saylorville emergency spillway discharge channel during the 1984 overflow

Figure 14. An upstream view of the Saylorville spillway discharge channel illustrating the "stair-step" erosional pattern exhibiting almost 30 ft of local relief

Saylorville Dam Spillway

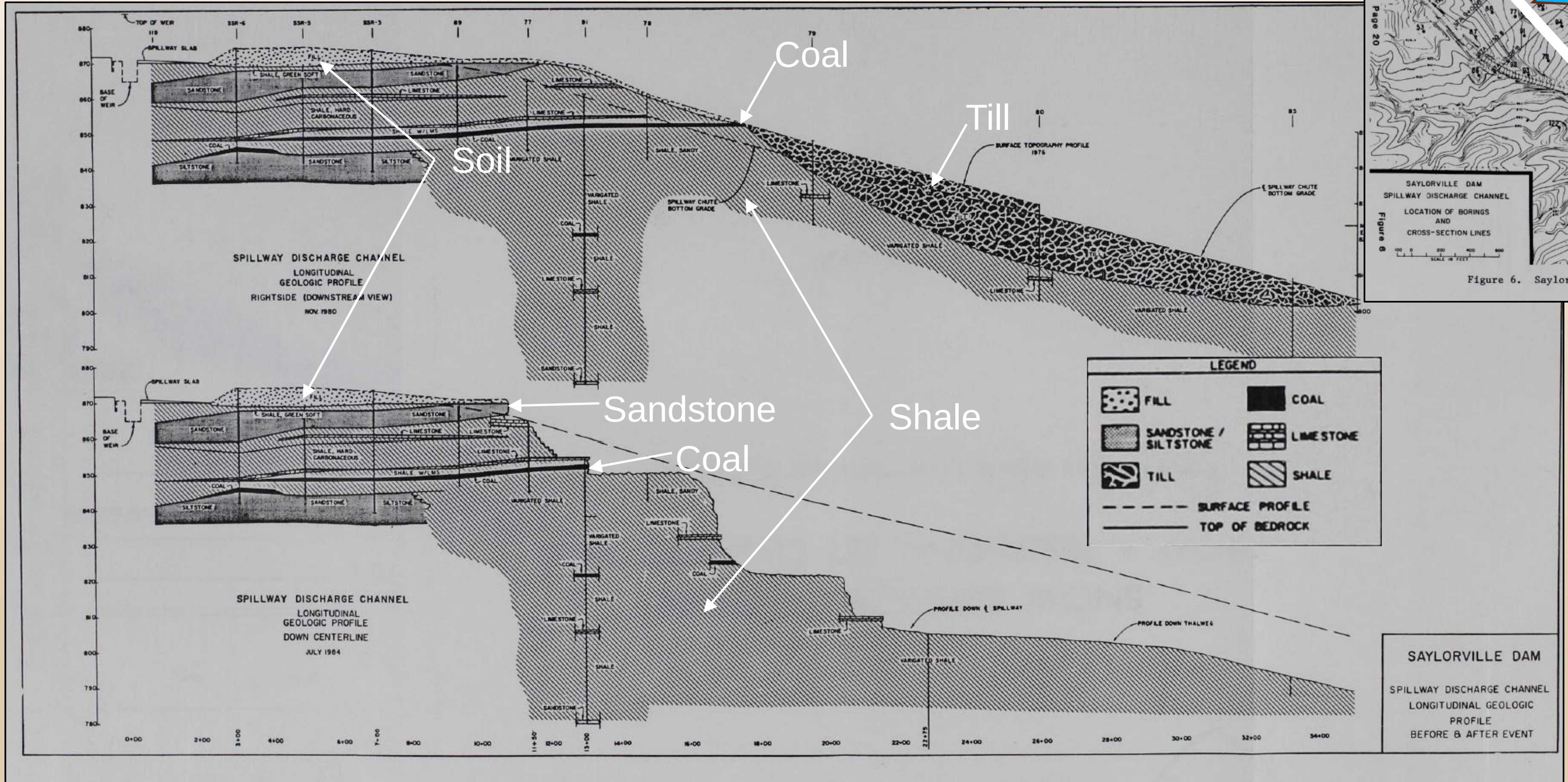


Figure 7. Saylorville emergency spillway discharge channel, longitudinal geological profiles (down centerline) before and after initial spillway overflow.

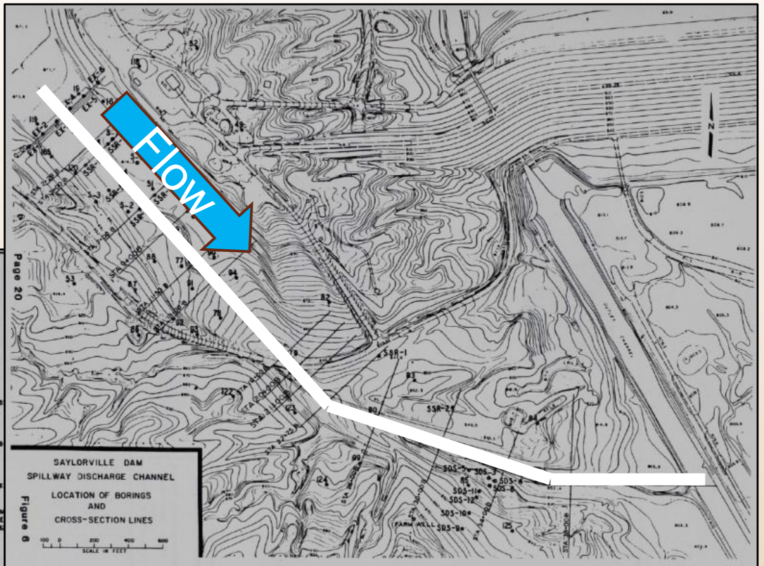


Figure 6. Saylorville Lake Dam. Locations of borings and cross-section lines, spillway discharge channel

Saylorville Dam Spillway

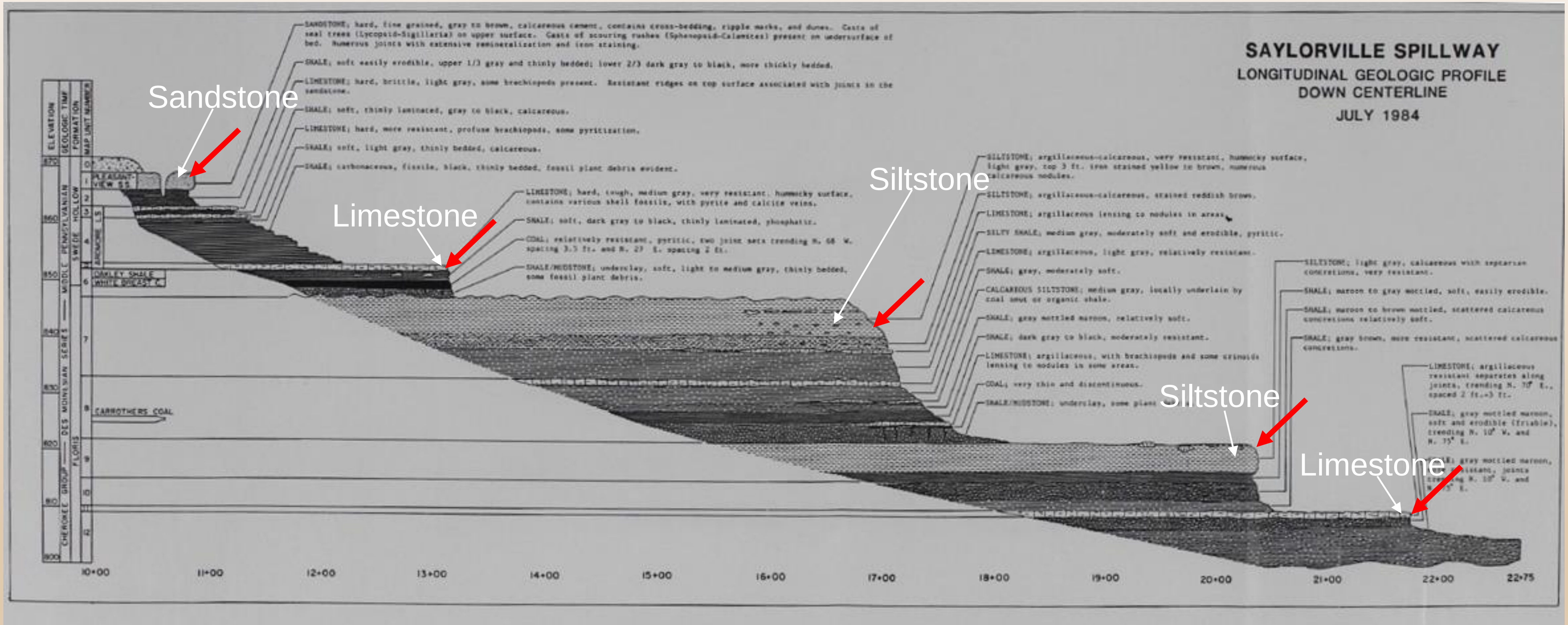


Figure 8. Detailed stratigraphy and lithologies underlying the lower portion of the Saylorville Dam emergency spillway discharge channel

Tuttle Creek Dam Spillway

- USACE (Kansas City) Dam in Kansas, in operation in 1962
- Controlled Crest, Lined Chute, Unlined Exit Channel
- Spillway is comprised of units of Limestone underlain by Shale
- 1993 Spillway Event
  - Spillway operated for 21 days
  - Peak Discharge of 60 kcfs
- Multiple Headcuts Formed and Advanced, controlled by limestone units

Tuttle Creek Dam Spillway

Tuttle Creek Dam Spillway

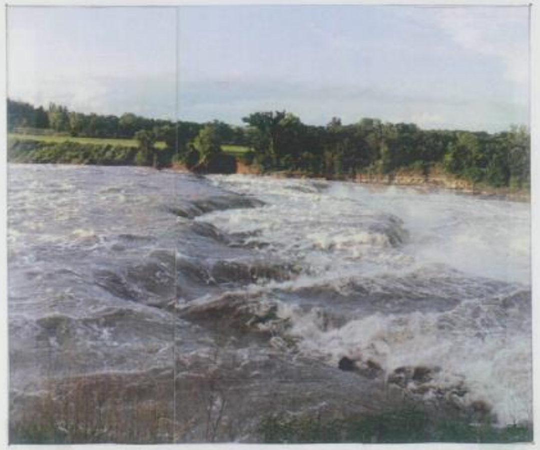


Figure B-14 Photo from Station 4 Showing Points H, G-1, and G-2, on 3 August 1993

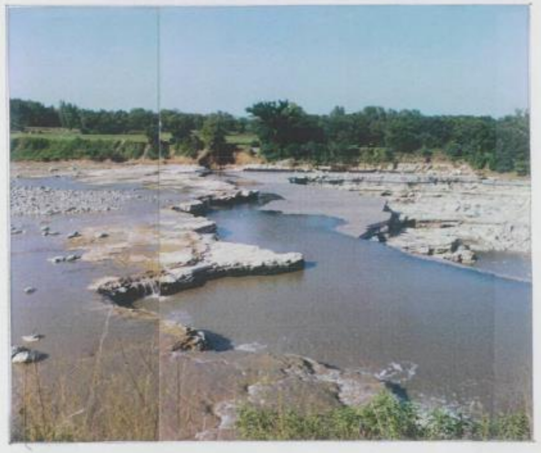
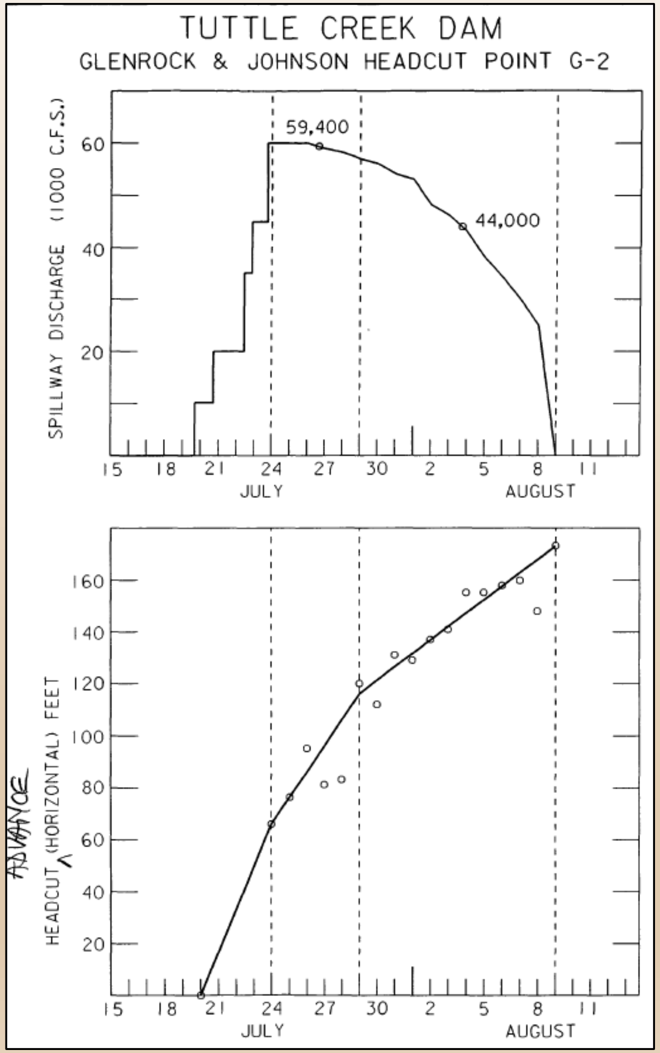
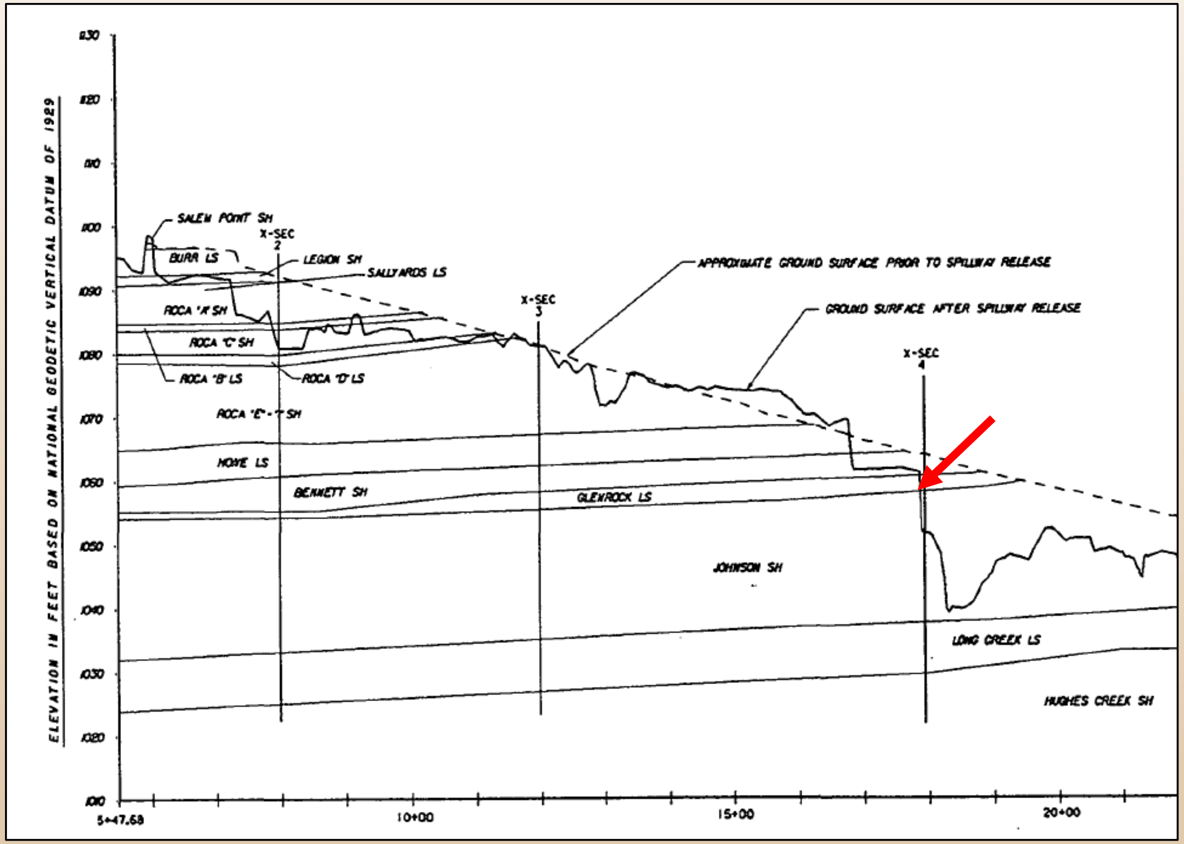


Figure B-15 Photo from Station 4 Showing Points H, G-1, and G-2, on 9 August 1993





Typical Event Tree

Typical Event Tree for Spillway Erosion

- Flows of Sufficient Energy to Fail Protective Lining or Cover or initiate erosion in unlined channels
  - Headcut Initiates/Advances
    - Defensive Measure do not exist or are ineffective
      - Intervention Unsuccessful
        - Head Cut Progresses to Reservoir (failing control structure or control section)
          - Breach downcutting and widening

Key Factors Affecting Vulnerability

Factors Affecting Vulnerability

- Erodibility of the spillway material (Soil or Rock)

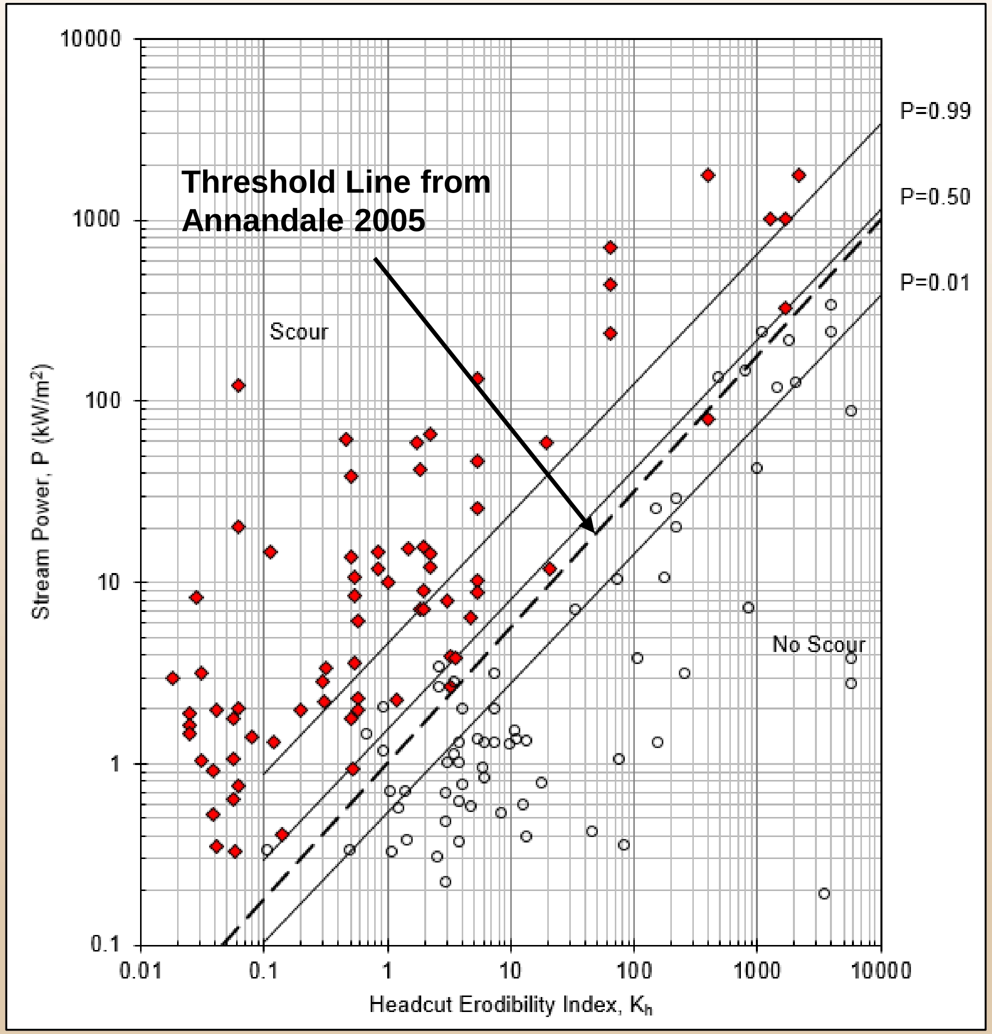
For Soil:
- ➢ Gradation
- ➢ Cementation
- ➢ Water Content
- ➢ Clay Content
- ➢ Vegetative Cover
- ➢ Surface Irregularity
- ➢ Detachment rate coefficient

For Rock:
- ➢ Joint Spacing
- ➢ Joint Orientation
- ➢ Joint Condition
- ➢ Lithology
- ➢ Rock Strength

- Energy of spillway/outlet flows
- Geometry of channel
- Energy dissipation
  - Jet break up/tailwater/stilling basin
- Location of headcut development
- Duration of spillway flow
- Length of scour/erosion pathway
- Armoring/Limitations on Transport
- Ability to intervene
- Inspection and Maintenance
- Presence and effectiveness of defensive measures

Analytical Methods

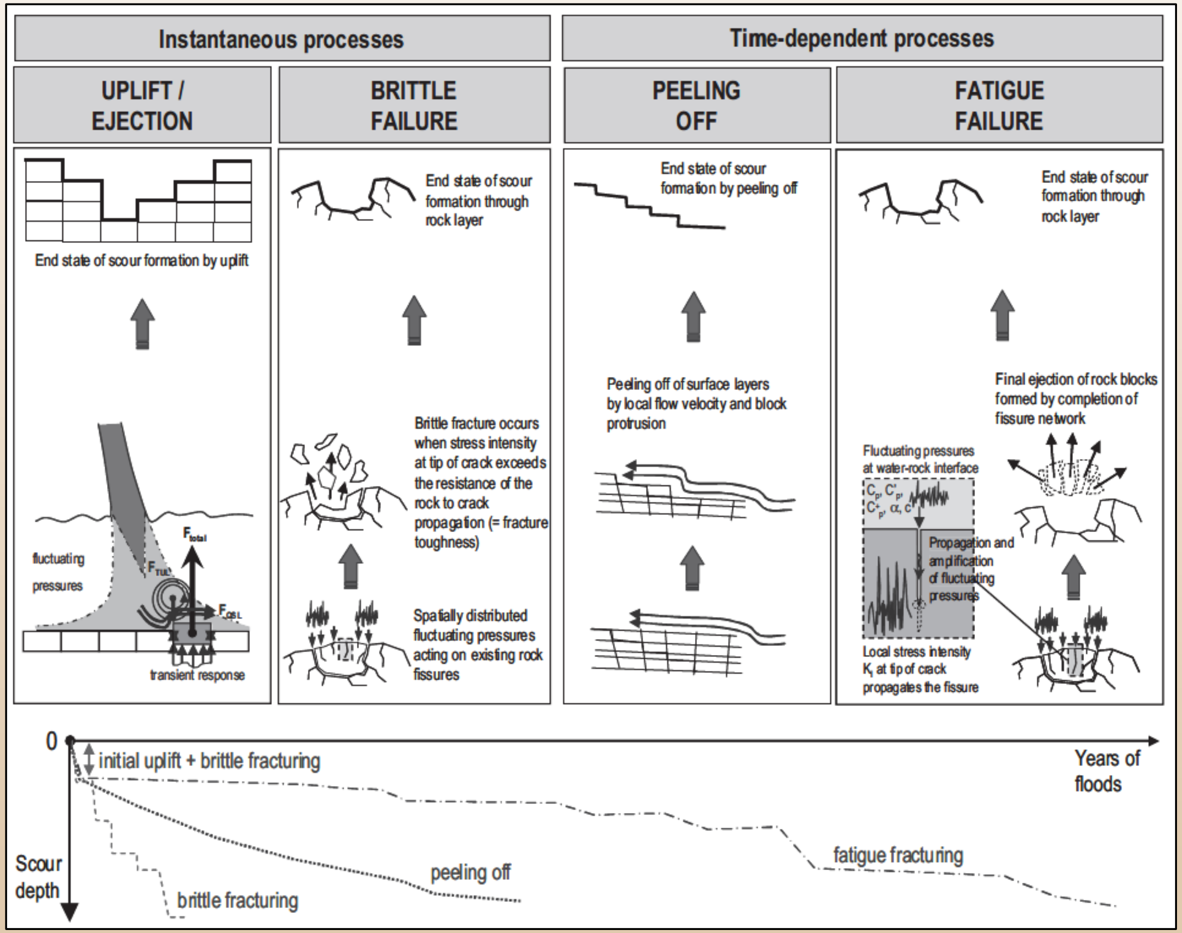
Analytical Methods (EIM)



Adapted from Wibowo and Murphy 2005

- The Erodibility Index Method (EIM) was developed by Dr. George Annandale
- Uses a semi-empirical relationship of Available Stream Power and Erodibility Index to estimate incipient scour (judgement required)
  - ➢ Erodibility Index is a geo-mechanical index
    - ✓ Mass Strength of Intact Rock (UCS)
    - ✓ Effective Block Size (RQD, # Joint Sets)
    - ✓ Effective Matrix Resistance (Joint Roughness, alteration)
    - ✓ Primary Jointing Orientation (Joint strike and dip)
  - ➢ Stream Power can be estimated:
    - ✓ Analytically with hydraulic formulas
    - ✓ Direct measurement of dynamic pressure fluctuations from scale model or prototype
- Figure Predicts initiation of Scour
- Method can predict ultimate scour (Potential limitation – does not directly predict rate of scour, although the magnitude of exceeding the threshold provides a relative indication)
- May need to iterate based on changing Erodibility Index at depth and/or tailwater effects

Analytical Methods (CSM)

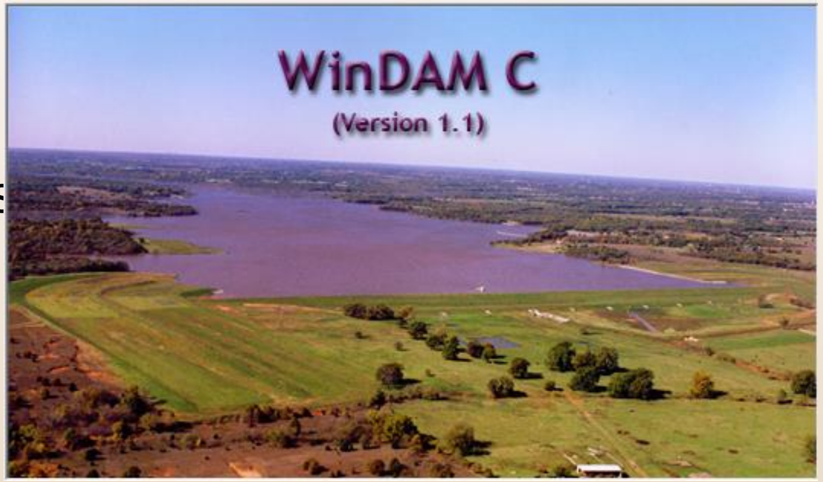


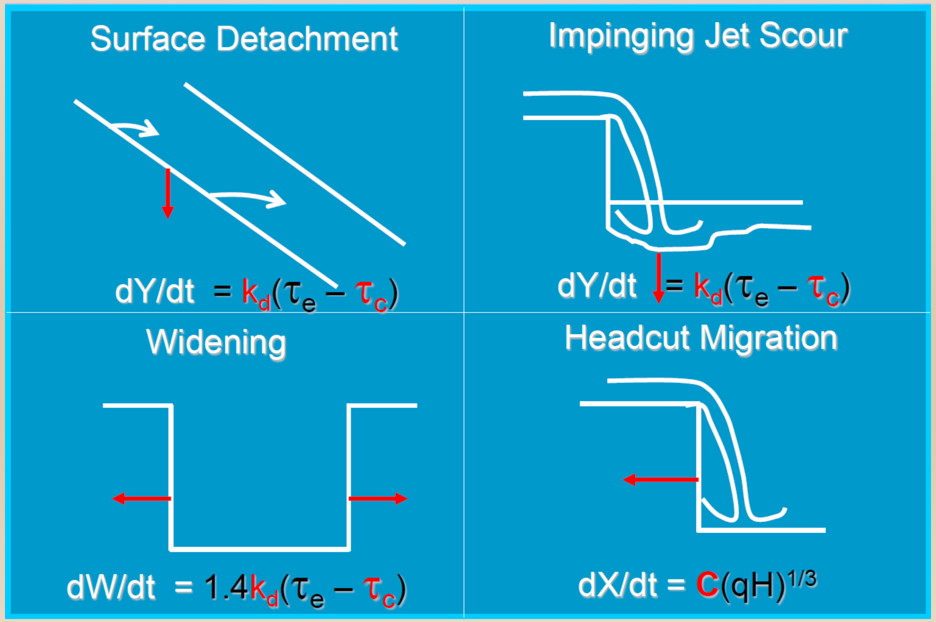
Bollaert (2010)

- The Comprehensive Scour Model (CSM) was developed by Dr. Eric Bollaert
- More Physically Based Approach
  - ➢ Represents separate detachment/transport mechanisms
    - ✓ Comprehensive Fracture Mechanics (CFM) Method
    - ✓ Dynamic Impulsion (DI) Method
  - ➢ Incorporates amplitude and frequency of fluctuating pressures explicitly
  - ➢ Method provides the ability to predict temporal aspects of scour
  - ➢ Potential limitations:
    - ➢ Idealized blocks
    - ➢ Dependent on confidence in geologic characterization

Analytical Methods (NRCS-WINDAM)

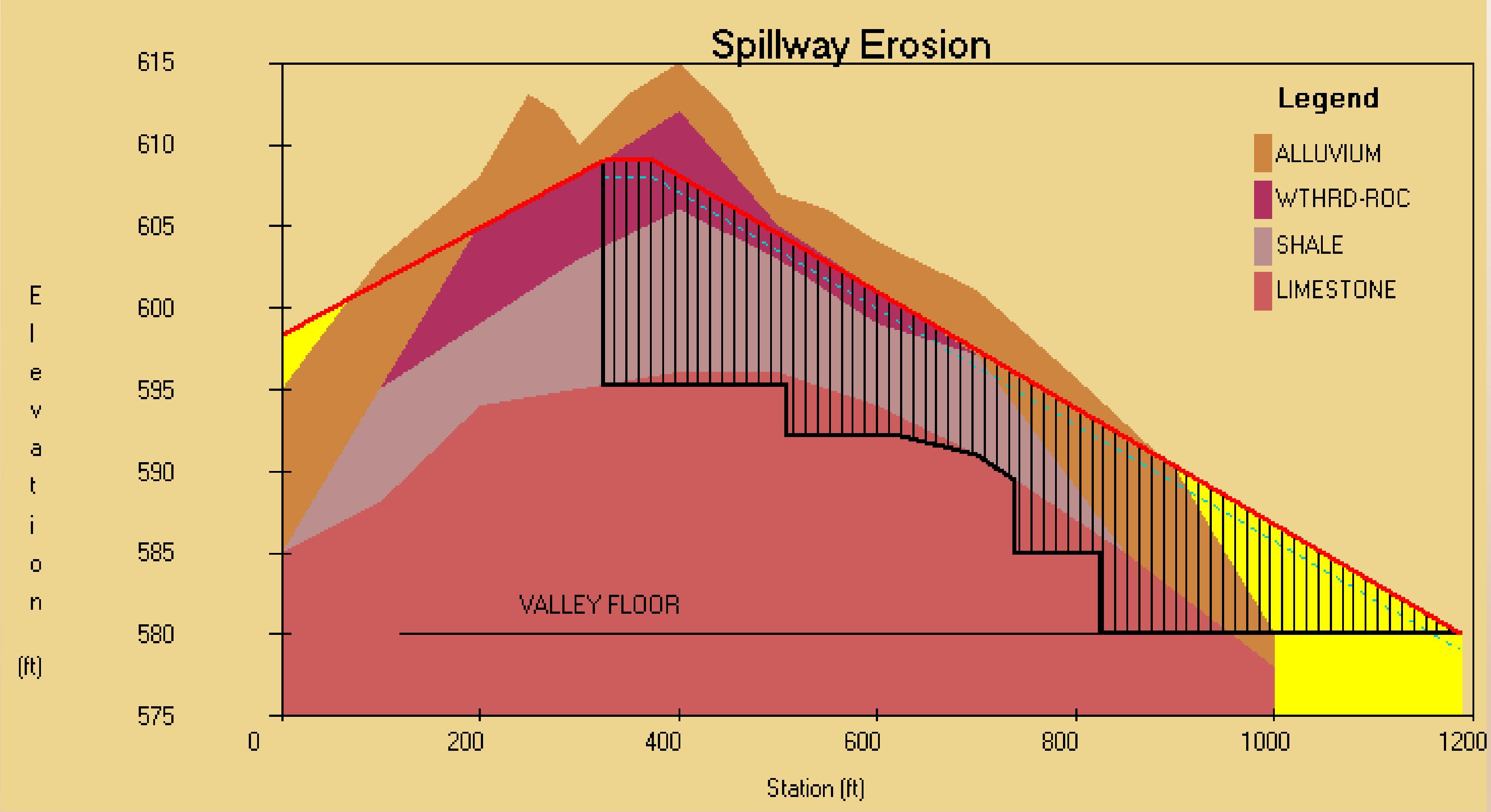
- Developed by NRCS
- Semi-Empirical Headcut Erosion Method
- Three Phases to Erosion/Scour for Soil Channels or Unlined Spillways
  - Cover Failure (vegetation or riprap)
  - Headcut Formation (downstream erosion)
  - Headcut Advance and Deepening (upstream migration)
- Erodibility Index is compatible
- Default values for threshold hydraulic attack and headcut advance rate are EMPIRICAL from a predominately soil dataset
- Allows for user defined:
  - Hydraulic Attack Thresholds
  - Headcut Advance Rates
- Simplified Hydraulics and Geology
- Not applicable to highly turbulent incipient flows





Analytical Methods (NRCS-WINDAM)

- Output Includes
  - Estimated Erosion Profile
  - Rate of erosion
  - Time series output
  - Breach
    - Geometry
    - Progression



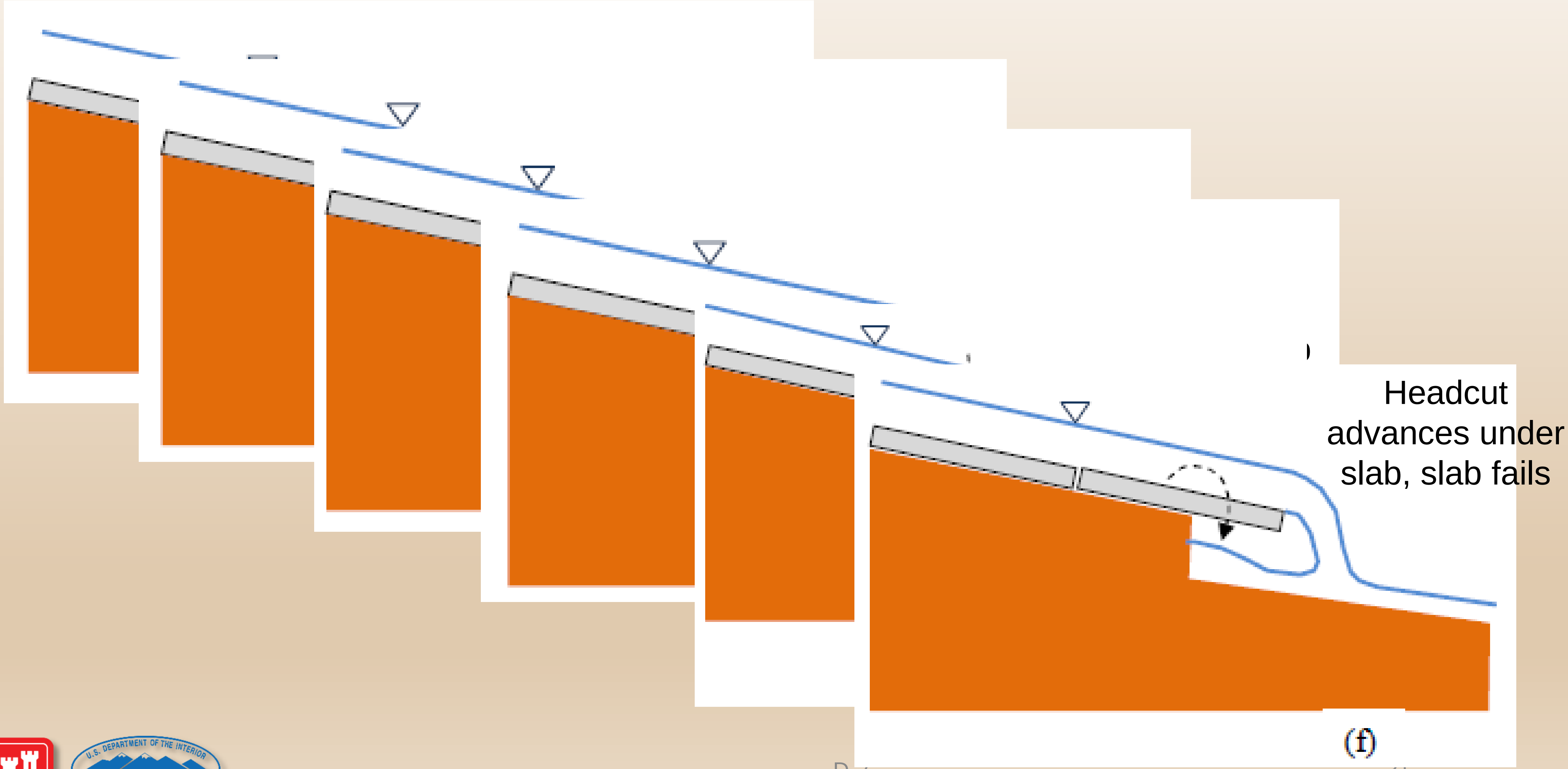
Analytical Methods (NRCS-WINDAM)

WINDAM Modeling Things to Remember

- Geometry and flow are as important as erodibility and other factors. More than one alignment may be necessary.
- Relationships are generally conservative if default values are used due to interpretation of empirical data (substantial enveloping)
- Flow Duration Relationship is Important, Extreme floods may not control
- Flow Concentrations due to lateral variations in geometry and geology are not considered
- User defined Thresholds and Advance Rates should be used if possible
- WINDAM is generally not appropriate to evaluate:
    - ➢Localized Scour and Undercut at a control structure or engineered slab
    - ➢Highly Turbulent Incipient Flow (e.g. stilling basins, plunge pools)

Cross Walk to other Potential Failure Modes

Cross Walk to other PFM's



Cross Walk to other PFM's

- Oroville Dam
  - Chute slab failure
  - Erosion
- Future investigations will provide additional insight into this PFM

Cross Walk to other PFM's

- Paradise Dam Spillway (Australia)
  - Small Apron
  - Endsill was compromised
  - Scour up to 40ft occurred on a near vertical face at the endsill
- Similar to the chute slab failure mode, progression potential affected by:
  - ability for the slab to cantilever
  - localized hydraulic characteristics
  - geology under the slab

Takeaway Points

- Unlined Spillway Erosion in Cohesive Materials Consists of 3-Basic Processes:
  - Particle Detachment, Particle Transport, and Turbulence Production (not in detail)
- Case studies illustrate the importance of:
  - Geology (individual units and lithology), Armoring, and Flow Frequency/Duration
- There are several methods for estimating scour for unlined spillways; but all are simplifications and **critical thinking and a foundational understanding of the process** cannot be understated
- The mechanisms for progression of other spillway and stilling basin PFM's are similar to the unlined spillway erosion PFM (other PFM's required to initiate erosion or complete the breach)
- Multi-Discipline Effort (Involve the right people)

Questions or Comments?

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